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Resolution Versus Field of View Trade-off for Monocular Night Vision Goggle Simulators

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Abstract

A field experiment was conducted to gain insight into the trade-offs between field of view (FOV) and resolution, with reference to the off-road mobility and target-detection capability of personnel using night vision goggles. Daytime simulators of night vision goggles were developed to represent all combinations of three levels of resolution (equivalent to 20/40, 20/80, and 20/120 Snellen acuities) and three FOVs (40°, 60°, and 80°). One product of the experiment was the formulation of a function that could be used to estimate human performance in traversing off-road terrain on foot. This trade-off function allows for the estimation of performance associated with any combination of resolution and FOV within the tested range. Another result was the identification of a significant interaction between FOV and resolution; for mobility errors, the effect of changes in resolution on performance increased as FOV decreased. For all dependent measures (errors, time, ratings, and targets), decreasing FOV had the most impact at the lowest level of resolution.

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INTRODUCTION

A clear, wide view of surroundings is generally needed for safe foot travel across rough, off-road terrain. At night, unaided vision is often useless in providing this type of view, and thus, safe travel is often jeopardized by an individual's inability to be forewarned of such terrain hazards as ditches, hidden rocks, and cliffs. This perceptual problem is especially pervasive during moonless nights. The use of night vision goggles (NVGs) can overcome some of the visual difficulties in traversing terrain, but these devices must be both cost effective and lightweight. For a given cost and weight, an improvement in one display parameter will usually adversely affect other display parameters.

Two display parameters that are often the focus of trade-off decisions are resolution and field of view (FOV). The trade-off between resolution and FOV with NVGs involves the following optical considerations. NVGs employ standard image-intensifier tubes that have a fixed number of imaging elements (i.e., the discrete channels of the microchannel plate, which is a component of the image intensifier tube). Because the number of imaging elements is fixed, there is a trade-off (inverse relationship) between resolution and FOV. If the FOV is increased, then resolution is decreased, and vice versa. Increasing the FOV without a corresponding decrease in resolution would require increasing the imaging element density or increasing the size of the intensifier tube. The size, weight, and cost penalties become very difficult beyond a 60° FOV. Weight increases rapidly with size, and a greater number of imaging elements implies substantially higher costs because of increased component cost and other factors. For these reasons, the present image-intensifier tube sizes and imaging element densities are accepted as fixed, and thus involve trade-off decisions between resolution and FOV.

Given the present image-intensifier tube sizes and imaging element densities, human performance data for resolution levels equivalent to Snellen acuities of 20/40, 20/80, and 20/120 and FOV ranges of 40°, 60°, and 80° were of interest to the Night Vision and Electronic Sensors Directorate and thus were important parameters in this study. The Snellen acuities of 20/40, 20/80, and 20/120 roughly correspond to typical NVG performance at scene illuminations of full moon, clear starlight, and overcast starlight, respectively. The 40° FOV is provided by current NVGs, while prototype NVGs providing a 60° FOV have recently been developed. The 80° FOV is the objective of NVG research and development programs that have recently commenced.

This type of human performance data could not be obtained from the considerable literature about resolution and FOV for several reasons.

The first reason is that the extant literature is oriented primarily toward aviation, target acquisition, and visual performance testing (e.g., Barfield, Rosenberg, & Furness, 1995; Donohue-Perry & Task, 1994; Kenyon & Kneller 1993; Dixon, Martin, Rojas, & Hubbard, 1990; Benzschawel & Cohn, 1985). The resolution and FOV literature suggests that the relative importance of resolution and FOV is highly dependent on the specific function performed by the human or the specific task. It therefore seemed unreasonable to conclude that these data would generalize adequately to off-road travel on foot.

A second reason that data from the extant resolution and FOV literature were insufficient to meet our objectives is that individual studies examined FOV exclusively or resolution exclusively. An important objective for this study was to obtain data about the relative importance of resolution and FOV when these two factors are varied independently. This would then allow the authors to obtain information about performance and preference when observers are provided with imagery that shows the visual effects of a reduction in resolution as a trade-off for a specific increase in FOV.

A third deficiency of the extant literature relates to general methodological shortcomings of research conducted before a study conducted by the authors (CuQlock-Knopp, Torgerson, Sipes, Bender, & Merritt, 1995) to evaluate off-road travel on foot as a function of NVG characteristics. In preparation for that study, a methodology was developed to evaluate the perceptual and motor components of off-road foot travel. The methodology isolated the effects of the quality of visual information provided to the observer from the effects of nuisance variables such as navigation ability, order, practice, and terrain course difficulty. Two studies were conducted using this methodology. Although the main objective of the studies was to determine the relative advantage of the ocular configuration of the NVGs used, these studies also served to validate the general methodology. The purpose of the present study was to determine the specific trade-off function between resolution and FOV for off-road movement on foot using this methodology.

METHOD

Experimental Design

Nine different Graeco-Latin squares were used in this study to examine the effects of the three levels of resolution and the three levels of FOV given in Table 1. The nine goggle types were counterbalanced across five factors: days, session, group, order, and course. In addition,

each goggle-course combination was counterbalanced across each day, and (across three days) each goggle-course combination was counterbalanced across each session. This counterbalancing scheme made goggle-type orthogonal to all the nuisance variables (days, session, group, order, and course).

Table 1

Nine Goggle Types

	Resolution		
Field of view (deg.)	20/40	20/80	20/120
40	Goggle 1	Goggle 4	Goggle 9
60	Goggle 7	Goggle 2	Goggle 5
80	Goggle 6	Goggle 8	Goggle 3

Independent Variables

The independent variable of resolution had three levels that corresponded to Snellen acuities of 20/40, 20/80, and 20/120. The independent variable of FOV also had three levels: 40°, 60°, and 80°. The nuisance variables of group, order, and course were used in this design so that the variation in performance attributable to goggle type could be isolated from the variation in performance attributable to these unavoidable but irrelevant variables.

The days variable allowed us to isolate the differences in performance that were related to the day that the participant completed the experiment. Likewise, the session variable allowed us to isolate that part of the participant's performance attributable to the session (morning, early afternoon, or late afternoon) that the participant completed the experiment. The course independent variable allowed us to assess the variation in performance attributable to differences in the three courses. (Multiple courses were used to ensure that a participant's performance did not vary over trials because he became more familiar with the specific characteristics of a given course.) The group independent variable allowed us to assess the performance variation attributable to differences between subject groups, differences that would be expected to occur only by chance or by any effects related to specific combinations of courses, goggles, and ordering. The order independent variable allowed us to assess the variation in performance attributable to the order of exposure to each one of the three goggles used by each participant.

Dependent Variables

Dependent Variable 1 (errors)

Eight types of errors were tallied by an independent observer (denoted as the "lane walker") who followed the participant as he traversed the course: (1) contact with an eye-level hazard, (2) contact with a ground-level hazard, (3) contact with a terrain contour hazard, (4) marked decrease in walking pace, (5) request for assistance, (6) stop, (7) stumble, and (8) other. Variable 1 is the total number of errors summed over all eight types made by the participant while he traversed the course.

Dependent Variable 2 (time)

Variable 2 is the total time taken by the participant in completing each course.

Dependent Variable 3 (ratings)

Variable 3 is the average of the participant's ratings of each goggle over seven individual items. Three of these items reflect the participant's rating of the warning afforded by the goggles in preventing his contact with eye-level, ground-level, and terrain contour hazard irregularities. One item reflects the utility of the goggles for target detection. The remaining three items reflect the participant's visual confidence, comfort, and his general feeling of the extent to which the goggles allowed timely forewarning of terrain hazards. Seven-point rating scales were used (1 was the lowest and 7 was the highest rating). These rating scales comprise Questionnaire A, which is included as Appendix A.

Dependent Variable 4 (target detection)

Variable 4 is the number of targets detected by the participant on each course. This variable was not of direct interest to this study but was included to motivate the participants to actively scan the environment, and thus help make the scenario used in the experiment more representative of the infantry environment.

PARTICIPANTS

Test Participants

Fifty-four male National Guard personnel between the ages of 24 and 54 participated in this experiment.

Lane Walkers

Half of the six lane walkers were National Guardsmen and the other half were psychology graduate students. All lane walkers were physically fit and well trained on the scoring procedures used for the experiment. Each lane walker was assigned to a specific course throughout the experiment.

The tasks of each lane walker were to instruct and aid the participant in fitting the goggles and then to follow him as he traversed the course. While doing this, the lane walker recorded the errors made by the participant, the time the participant took to complete the course, and the number and types of targets the participant detected. The lane walker did not wear NVG simulators for the experiment.

Interviewer

The interviewer was the person responsible for administering the questionnaires[1] to the participants.

APPARATUS

Night Vision Goggle Simulators

To investigate the effects of resolution versus FOV, nine types of simulated NVGs were constructed to provide daylight retinal images similar to those provided by actual NVGs during nighttime conditions. All goggle simulators were made for binocular viewing, with a provision for blocking the less preferred eye when used to simulate monocular night vision goggles during no-moon conditions. The nine resolution-versus-FOV combinations shown in Table 1 were constructed.[2] An example of one of the simulators used in this study is shown in Figure 1. The monocular, preferred eye configuration was used exclusively to avoid the variation in FOV overlap, which would have resulted in the binocular mode from participants having different interpupillary distances. It is also noted that the most recent NVGs developed for infantry use have in fact been monoculars.

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[1] A second questionnaire is described in the Procedure section.

[2] In addition to the nine simulator goggles, one duplicate of each resolution and FOV type was constructed, making a total of 18 goggle simulators. These nine duplicates permitted flexibility in running participants simultaneously, as well as providing backup in case a particular goggle simulator was damaged during an experimental run.

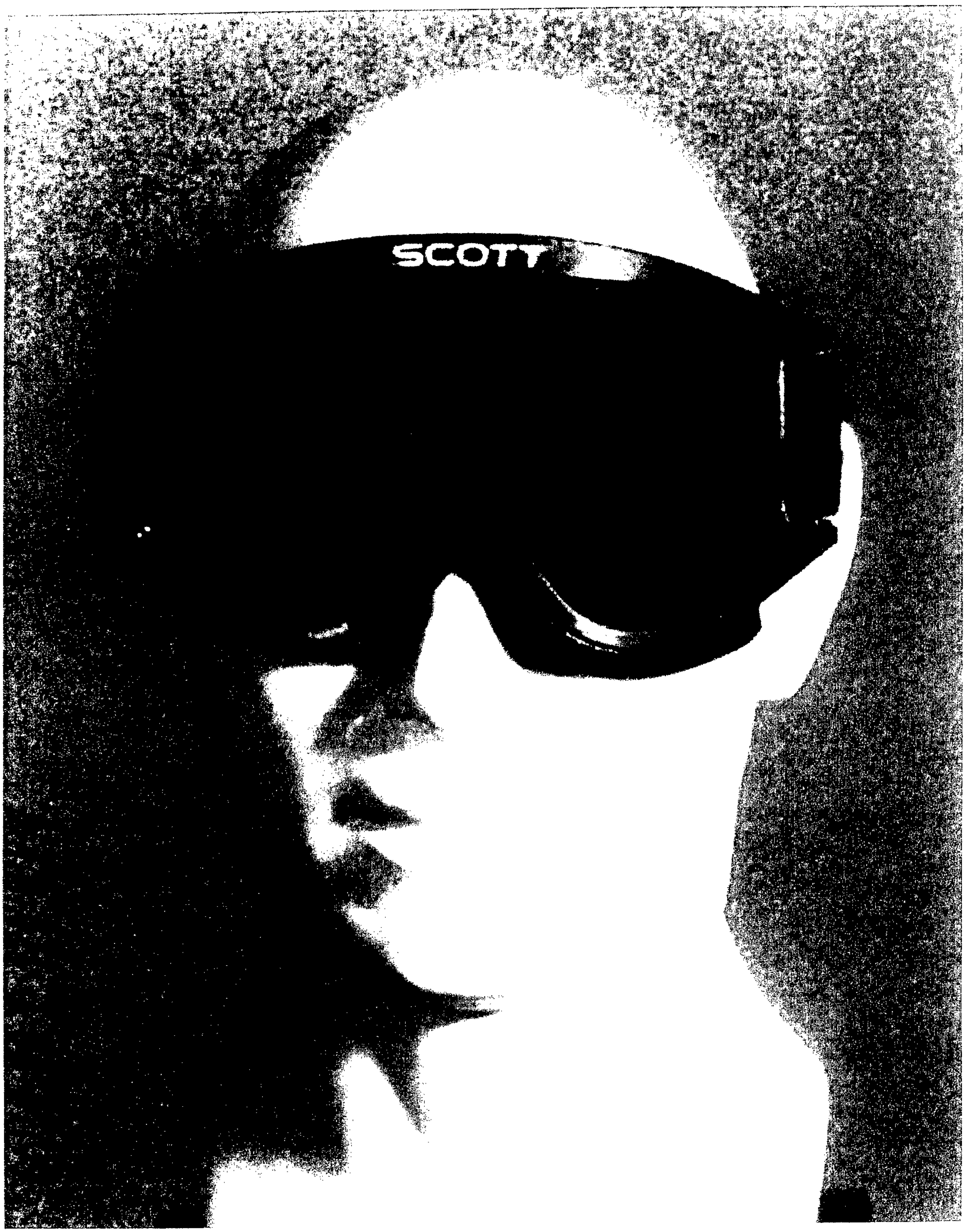

Figure 1. One of the NVG simulators used to examine the trade-off relation between resolution and FOV.

Method of Construction

Simulated night vision goggles were constructed using ski goggles fitted with an opaque visor containing two circular holes, one in front of each eye, and fitted with two layers of green filter material (Roscolux No. 874, medium green, each layer with photopic transmittance 9.5%, peak photopic wavelength 520 nm). This produced a circular green FOV with approximately 1% transmittance (ND2) from the ambient daylight scene, simulating the circular intensified FOV provided by standard NVGs. The visual area outside the circular green FOV was opaque, providing no visual input, as would be the case during no-moon conditions.

Ski goggles used to construct the simulators were Scott "Powder OTG" (over the glasses) goggles, with double-layer thermal anti-fog lenses to reduce fogging, soft foam for facial comfort, and a headband clip for ease in donning the goggles.[3] The ski goggles also have extensive porous foam areas around top, sides, and bottom of the lens to let the wearer's water vapor escape and thus minimize fogging. The lens were treated on the inside with Scott Absorb2 anti-fog formula. Specific information about the resolution simulation method, the FOV simulation method, and differences between the NVG simulators and actual NVGs is provided in Appendix B.

Human Targets

Two male civilians, dressed in summer battle dress uniforms (BDUs) and winter field jackets, served as moving targets for each course. Each human target moved to a different course location once per trial; therefore, each participant could detect a maximum of four human targets per course.

Inanimate Targets

Three silhouette figures dressed in summer BDUs were placed on each of the three courses. The BDU clothing was stuffed with plastic bubble wrap to fill the body of the target. Figure 2 shows an example of one of the inanimate (silhouette) targets in the forest setting.

Test Site

A field experiment was conducted during the day at Camp Finney of the Broad Creek Memorial Scout Reservation in Harford County, Maryland. The test area consisted of meadows and woods of mixed deciduous and coniferous trees with a variety of terrain hazards to foot travel, such as drop-offs, berms, and ditches.

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[3] Previous simulator goggles based on welding goggles were found to be uncomfortable for longer wearing times and tended to fog with exertion.

Figure 2. An example of a silhouette target in the forest setting.

Three different 1-kilometer courses (Course A, Course B, and Course C) were developed for the experiments. White, 9-inch circular plates were mounted on trees along the course to mark the path the participant should follow. A rectangular piece of black tape was affixed to the center of each plate to improve the participant's ability to see the plates against the forest background.

On the average, the plates were 9 feet apart. All three courses were originally designed to be traversed in fewer than 30 minutes at night;[4] the typical daytime traversals with the NVG simulators required 15 to 20 minutes. The courses were also designed to provide adequate changes in terrain to allow ample opportunities to check hazard-avoidance performance.

A practice course was used to show the participants how the targets would appear against a forest background. The course was 100 feet long through a dense forest of sapling trees and bushes. One silhouette target was placed on the course.

PROCEDURES

Preliminary

The lane walkers were trained in the error-scoring, timing, and target-detection procedures used during the test. Each of the lane walkers traversed the course assigned to him in the daylight to ensure his knowledge of the terrain and his knowledge of the locations of the targets. The authors conducted two pilot tests to give the lane walkers extensive experience in scoring and timing the participants and to determine the adequacy of the testing procedures.

Testing Procedures

The counterbalancing scheme used to execute the experimental design is depicted in Table 2. On each of the three days listed in this table, there were three sessions: a morning session beginning at 0930, an early afternoon session beginning at 1200, and a late afternoon session beginning at 1430. For each session, each participant used one goggle of a subset of three of the nine goggles defined by the resolution-FOV combinations in Table 1. For the orders (first, second, or third), the participants traversed the course A, B, or C, wearing the type of goggles that is indicated by the number next to the letters in the table (e.g., 1A). Last, the numbers in parentheses represent the participant number. The entire counterbalancing scheme was repeated once for a total of 54 participants.

Randomization procedures were used to assign the participant numbers (1 through 27) to the 54 participants. Thus, on Day 1, Session 1, Participant (1) first wore Goggle 1 on Course A, then Goggle 2 on Course B, and finally, Goggle 3 on Course C.

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[4] These same courses were used in a previous study; this 30-minute criterion was important for that study.

Table 2

The Counterbalancing Scheme for the Experimental Design

		Day 1 Order				Day 2 Order				Day 3 Order		
		1st	2nd	3rd		1st	2nd	3rd		1st	2nd	3rd
Session 1												
	(1)	1A	2B	3C	*(10)*	5B	6C	4A	*(19)*	9C	7A	8B
	(2)	6B	4C	5A	*(11)*	7C	8A	9B	*(20)*	2A	3B	1C
	(3)	8C	9A	7B	*(12)*	3A	1B	2C	*(21)*	4B	5C	6A
Session 2												
	(4)	4A	5B	6C	*(13)*	8B	9C	7A	*(22)*	3C	1A	2B
	(5)	9B	7C	8A	*(14)*	1C	2A	3B	*(23)*	5A	6B	4C
	(6)	2C	3A	1B	*(15)*	6A	4B	5C	*(24)*	7B	8C	9A
Session 3												
	(7)	7A	8B	9C	*(16)*	2B	3C	1A	*(25)*	6C	4A	5B
	(8)	3B	1C	2A	*(17)*	4C	5A	6B	*(26)*	8A	9B	7C
	(9)	5C	6A	4B	*(18)*	9A	7B	8C	*(27)*	1B	2C	3A

Each set of three participants began the experiment with a briefing about the purpose of the study and by reading and signing a consent form. Each was then tested for at least 20/40 visual acuity. The Snellen chart was used to screen for the minimum acuity requirement. All participants were allowed to choose the eye to use to view the environment. Next, the participant donned the type of goggle appropriate for the first run in his group assignment. A white opaque eye patch was used both to block the view in the non-preferred eye and to absorb perspiration from the participant.

Each participant preceded his lane walker to the practice course and traversed it. (The participant traversed the practice course one time only before his first course of record.) Next, the participant went to the starting point of Course A, B, or C. The lane walker gave the direction to the participant to search for targets while traversing the course as quickly as possible. The participant was not told how many targets were on each course.

The lane walker started a stopwatch as soon as the participant took his first step, and he recorded the time taken by the participant to complete each segment of the course on a score sheet. The lane walker also noted on the score sheet each instance of an error (stumbles, stops, etc.) made by the participant in completing the course and the number and types of targets detected. (This score sheet is included as Appendix C.) After finishing the course, the participant and the lane walker returned to the base camp tent.

The interviewer administered Questionnaire A to the participant to record his subjective ratings of the goggle. The participant then donned his next goggle and followed his new lane walker outside to begin traversing the next course. This procedure was repeated until all three courses, along with their associated Questionnaire A forms, were completed.

Following this, the participant completed Questionnaire B, a supplemental questionnaire used to provide a rank for each of the three goggles used by the participant. These ranks were collected as descriptive data to supplement the information provided by the major dependent variables. This questionnaire is included as Appendix D.

After this questionnaire was completed, the participant's eye dominance was tested. The participant's performance in this experiment was completed after this test. The participant was paid a total of $65.00 for his test participation.

Three sets of three participants were tested each day. A chart showing the sequence of events for a set of three test participants is presented as Appendix E. The subsequent set of participants began their testing immediately after the previous set of participants left the camp. The six days of testing were completed within two weeks in January 1995.

RESULTS

The information provided in this section illustrates the specific pattern of results for each major dependent measure as a function of the resolution and FOV characteristics of the NVGs simulators used. Supplemental, descriptive data are also provided in this section.

Analyses of variance (ANOVAs) were conducted on the three major dependent variables (errors, time, and ratings) and on the target-detection dependent variable to confirm that we had selected ranges of resolution and FOVs to which the dependent measures would be sensitive. In most instances, both the resolution and the FOV main effects were significant. In addition, the interaction for the dependent variable, error, was significant. The effect of changes in resolution

on performance increased as FOV decreased.[5] The summary tables are presented in Appendices G, H, I, and J.

Errors

The means of the number of errors (averaged across error type and participants) are presented in Table 3. These means are also plotted in Figure 3. (All three dimensional charts are shown using the perspective that allows all data bars to be visible.)

Table 3

Mean Errors

Field of view (deg.)	Resolution 20/40	20/80	20/120	Means
40	8.44	10.67	13.83	10.98
60	7.06	8.67	8.61	8.11
80	6.94	6.44	7.28	6.89
	7.48	8.59	9.91	8.66

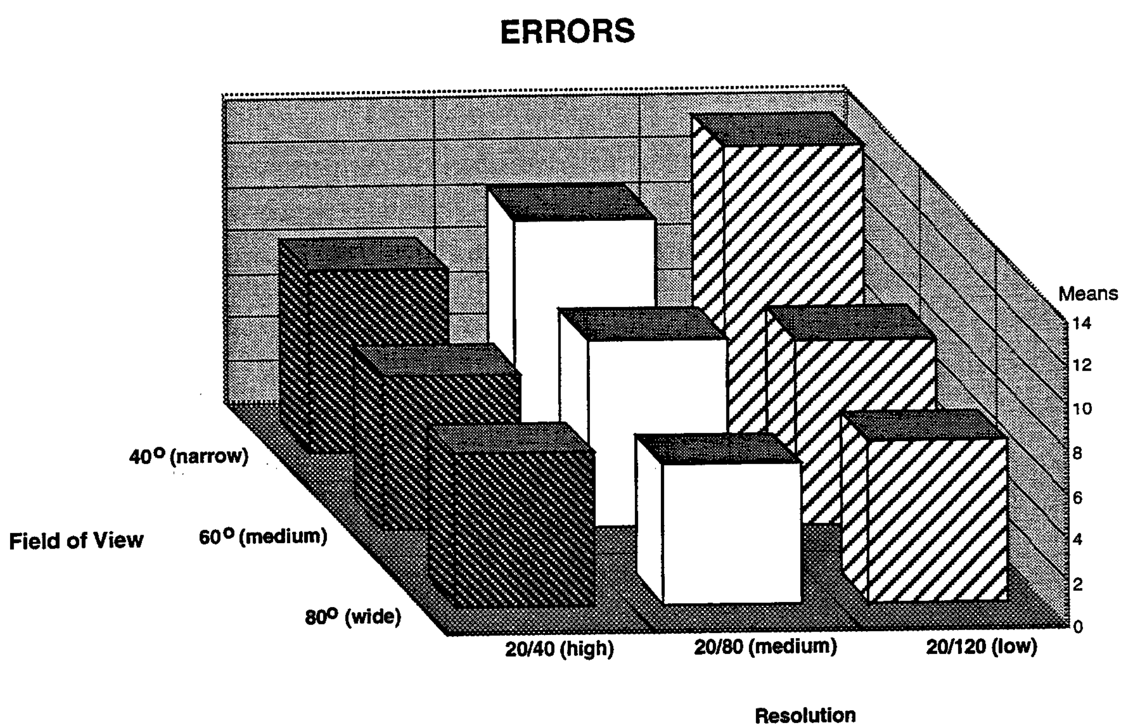


Figure 3. The means of the number of errors, averaged across error type and test participants.

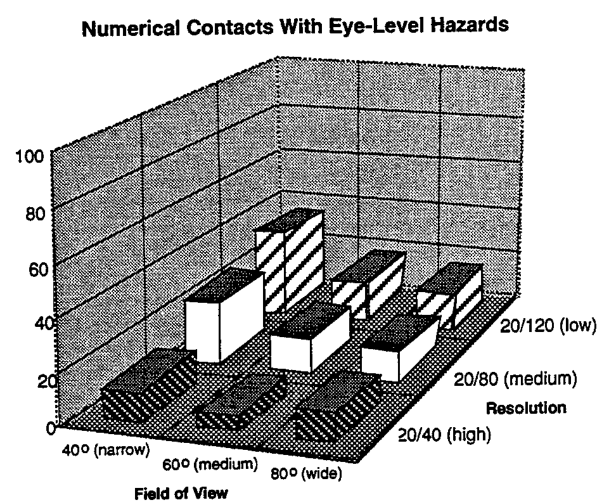
[5] The analyses of the simple main effects for all the independent variables are presented in Appendix F.

Table 4 contains the means (across participants) for each type of error type separately. Separate plots for each error type are provided in Figure 4.

Table 4

Sum of the Errors Across FOV and Resolution

FOV	40°			60°			80°		
Resol.	20/40	20/80	20/120	20/40	20/80	20/120	20/40	20/80	20/120
				Errors					
Eye	12	25	34	6	14	17	11	12	15
Ground	72	64	95	65	61	65	67	55	57
Contour	5	9	12	4	6	18	5	5	7
Pace	22	36	23	14	21	19	12	14	19
Assist	2	8	3	6	5	3	3	5	2
Stops	24	35	56	22	32	24	15	13	17
Stumble	11	14	20	9	9	7	10	9	12
Other	4	1	6	1	8	2	2	3	2



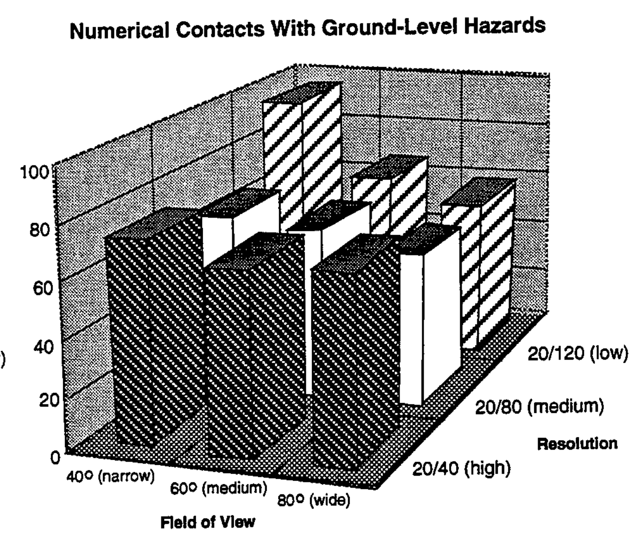


Figure 4. Plots of the means (across participants) for each type of mobility error.

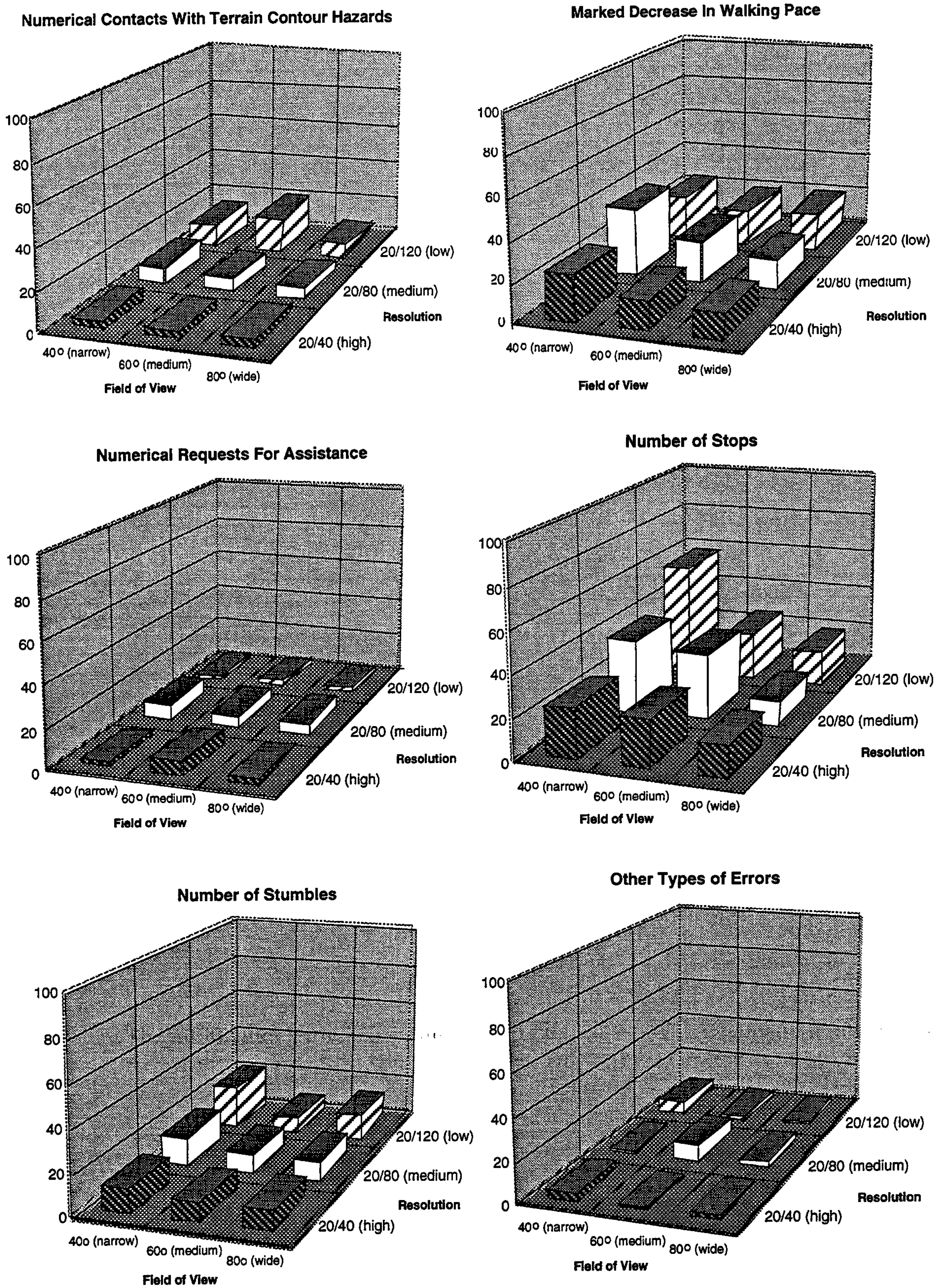


Figure 4 (continued).

Time

The means (across participants) of elapsed time in minutes to traverse the courses for each of the nine goggle types are presented in Table 5. These means are also plotted in Figure 5.

Table 5

Mean Times

	Resolution			
Field of view (deg.)	20/40	20/80	20/120	Means
40	14.64	16.75	15.97	15.79
60	12.93	14.47	16.24	14.55
80	13.85	13.71	13.40	13.65
	13.81	14.98	15.20	14.66

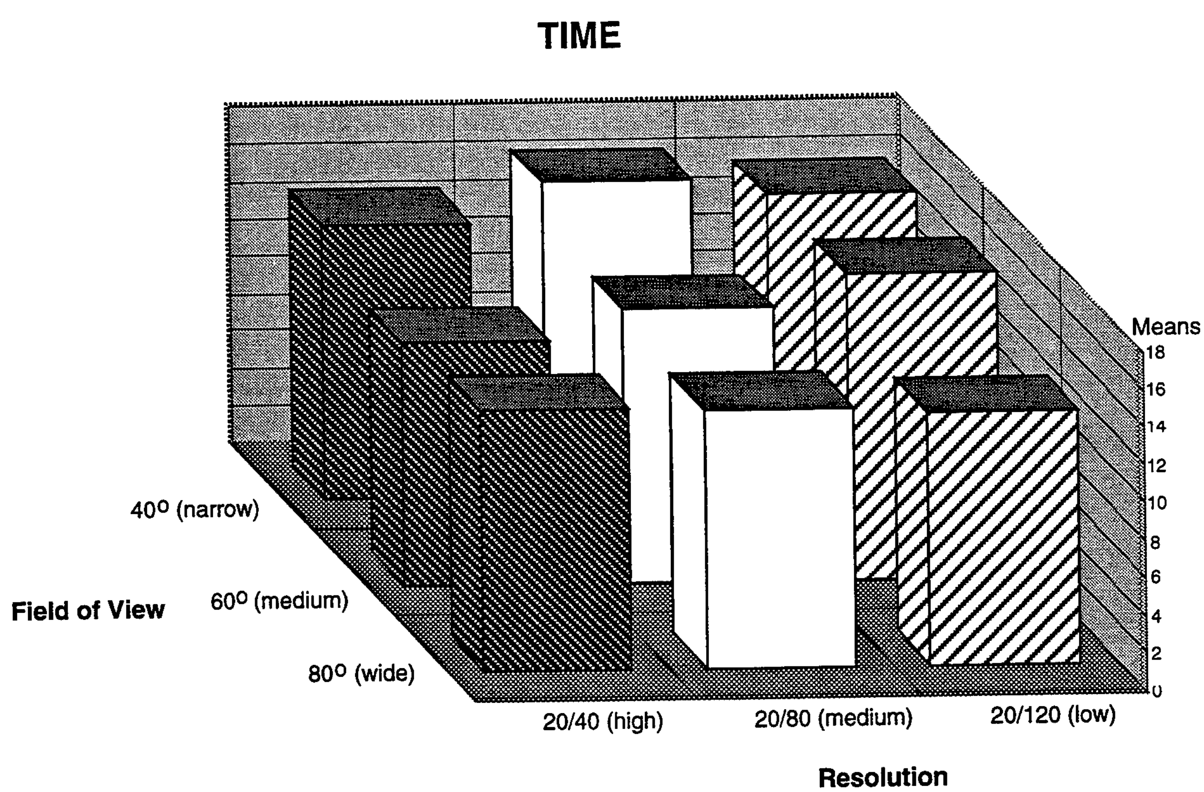


Figure 5. The means (across participants) of elapsed time in minutes to traverse each course for each of the nine goggle types.

Ratings

The last of the major dependent measures to be reported is the ratings. The participant rated each goggle on a 7-point scale (1 = poor, 7 = good performance) for seven qualities: the warning afforded by the goggles in preventing the participant's contact with (1) eye-level hazards, (2) ground-level hazards, (3) terrain contour hazard irregularities, (4) target detection, (5) confidence, (6) visual comfort, and (7) general feeling that the goggles allowed timely forewarning of terrain hazards. The seven individual items in Questionnaire A were summed to obtain a single score for each participant for the entire questionnaire. The average of the seven questionnaire items for each of the goggles are given in Table 6 and plotted in Figure 6. (A table showing the means across participants for each questionnaire item for each resolution and FOV level is given as Table K-1 in Appendix K.)

Table 6

Mean Ratings

	Resolution			
Field of view (deg.)	20/40	20/80	20/120	Means
40	5.52	4.69	3.48	4.56
60	5.48	5.17	4.93	5.19
80	5.95	4.59	5.23	5.26
	5.65	4.82	4.55	5.00

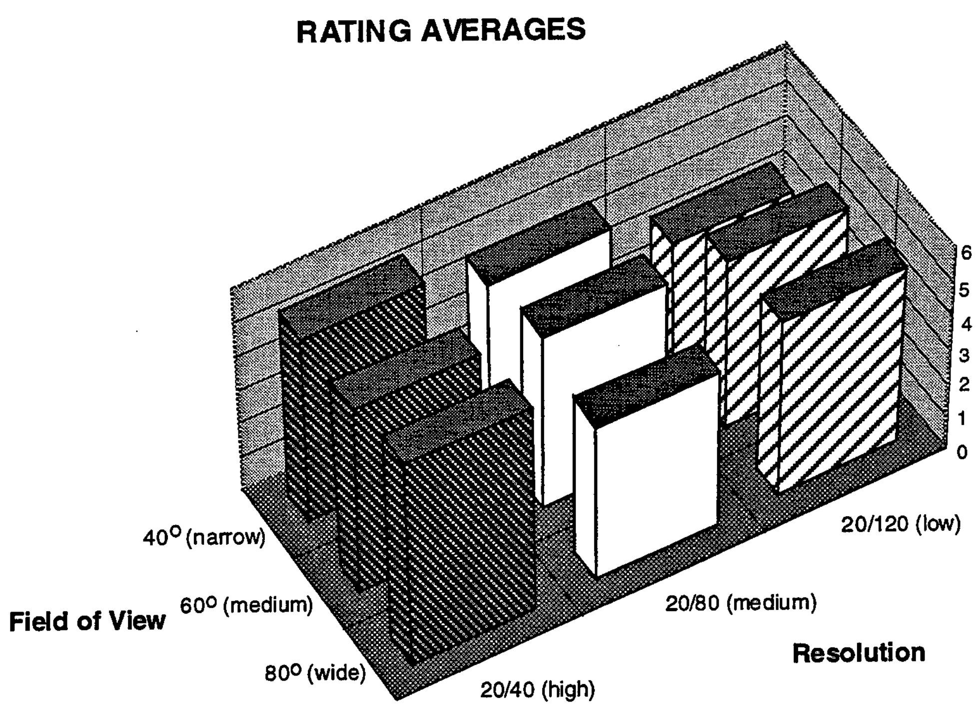


Figure 6. The average of the seven Questionnaire A items for each of the nine goggle types.

Ranks

After the participant finished his third course, he was asked to rank each goggle relative to the other two goggles for five aspects of goggle utility: depth perception, level of comfort, target detection, hazard detection, and environmental awareness. One additional ranking was made to obtain the overall preferences of the participants. The participant was asked to write a response to the item "Write 'best' under your first choice of goggles to wear during a night mission; write 'worst' under your last choice."

No analyses that would have involved summary statistics across levels of resolution or levels of FOVs were completed because each participant used only three of the nine total goggles. Thus, when the participant ranked a goggle, it was ranked relative only to two other goggles. Comparing the rank of a goggle in one subset against a rank of a goggle in another subset would be meaningless. The mean ranks for each aspect of goggle utility are given in Table 7; the mean ranks (averaged across these six ranks) are given in Table 8. Rankings of "3," "2," and "1" corresponded to the "best," "middle," and "worst" ranks, respectively.

Table 7

Ranks of the Nine Goggle Types

Field of view (deg)	Resolution 20/40	20/80	20/120
		Depth perception	
40	2.44	1.61	2.00
60	2.78	1.78	1.61
80	2.78	2.17	1.78
		Level of comfort	
40	2.39	1.56	1.17
60	2.83	1.94	1.61
80	2.83	2.11	1.67
		Target detection	
40	2.56	1.72	1.06
60	2.89	1.72	1.56
80	2.72	2.06	1.72
		Hazard detection	
40	2.33	1.50	1.06
60	2.83	1.89	1.61
80	2.89	2.11	1.78
		Environmental awareness	
40	2.61	1.56	1.11
60	2.83	1.67	1.56
80	2.89	2.00	1.72

Table 8

Mean Ranks of the Nine Goggle Types

Field of view (deg.)	Resolution 20/40	20/80	20/120	Means
40	2.39	1.66	1.24	1.76
60	2.69	1.83	1.66	2.06
80	2.69	2.08	1.78	2.18
	2.59	1.86	1.56	2.00

Target Detection

The target-detection dependent measure was not considered one of the major dependent variables. It was included in the study as a motivating device to ensure that the participants scanned the environment. Table 9 provides the mean number of targets detected, averaged across target type (human and silhouette) and participant. Figure 7 provides a plot of the data.

Table 9

Target Detection

Field of view (deg.)	Resolution 20/40	20/80	20/120	Means
40	4.61	4.78	3.22	4.20
60	4.94	3.94	4.83	4.57
80	5.44	4.94	4.50	4.96
	5.00	4.55	4.18	4.58

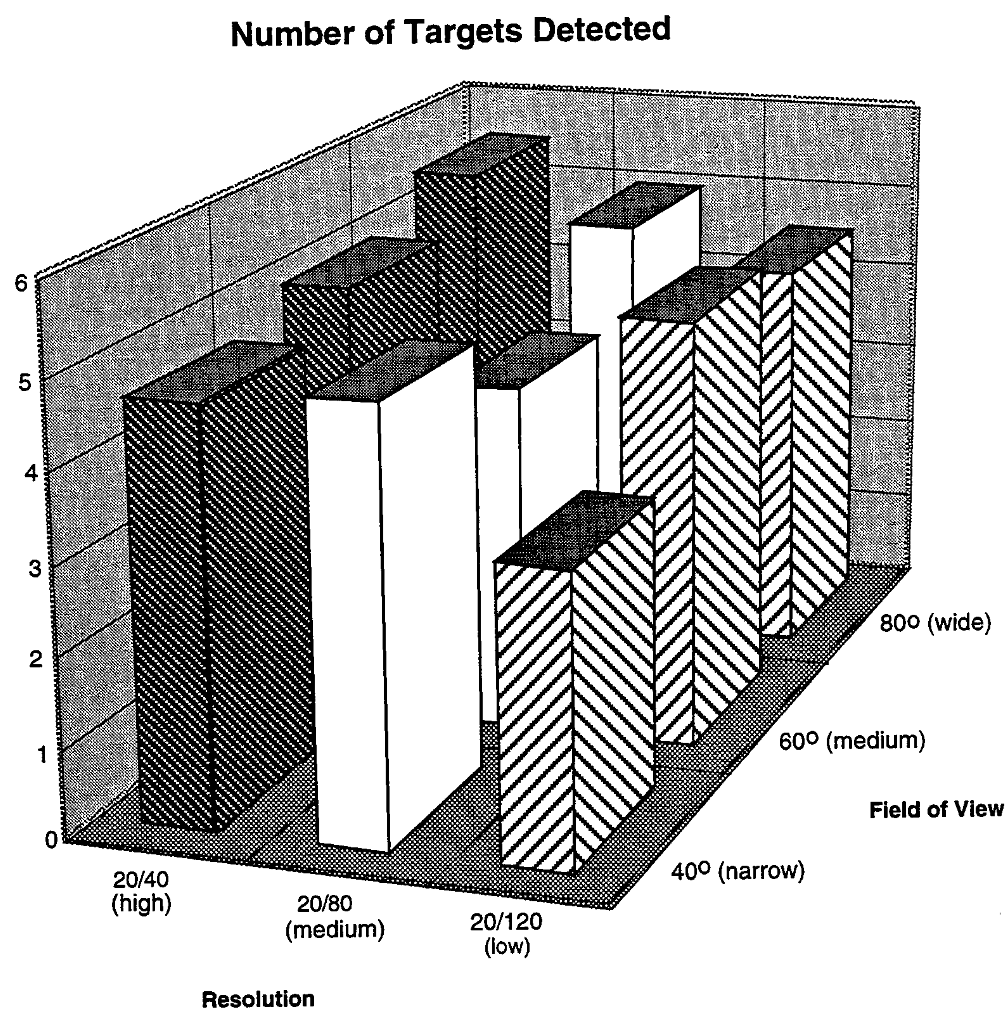


Figure 7. The mean number of targets detected, averaged across target type (human and silhouette) and test participant.

TRADE-OFF RELATIONS BETWEEN FOV AND RESOLUTION FOR MOVEMENT ERRORS

The procedures given below are based on the data of this study. They enable one to estimate the error rate for a goggle having any combination of FOV and resolution within the ranges examined. The dependent variable, error, was chosen for the examples because it seemed to provide the most consistent and reliable data.[6]

Table 3 gives the average raw scores for the nine conditions examined (3 levels of FOV x 3 levels of resolution). A main effects model was used to minimize random error. Thus, only the

---

[6] Note that the exact number of errors is specific to this experiment because of such factors as the specific terrain features or the length of the course. These numbers are only useful as a comparative measure of the relative performance between resolution and FOV values.

marginal means (row, column, and grand mean) were involved in developing the procedures for determining the trade-off relationships.[7]

Let

X_i = Average number of errors for the i^{th} FOV level over all resolution levels

Y_j = Average number of errors for the j^{th} resolution level over all FOV levels

M = The grand mean for errors over all conditions. Then the main effect model is

$$D_{ij} = (X_i + Y_j - M..)$$

where

D_{ij} = the estimated number of errors for the i^{th} FOV level and the j^{th} resolution level.

Figure 8 gives the plot of X_i (ordinate) versus FOV (abscissa). A curve has been fitted to these three points also. This curve can be used to obtain the estimated X value for any FOV level covered by the experimental situation.

Figure 9 gives the corresponding plot of Y_j (ordinate) versus resolution (abscissa). A slightly curved line has been fitted to the three points. The curve can be used to obtain the estimated Y value for any level of resolution covered by the experimental situation.

Two examples of the use of the two figures are given below, along with the main effects equation for the prediction of D_{ij},

$$D_{ij} = X_i + Y_j - M$$

<u>Example 1.</u>

Determine the combinations of FOV level and resolution level that will yield an estimated D_{ij} (estimate of errors) of some given value, for instance, 7.7. From Table 3, the grand mean for the error data is seen to be 8.66.

1. $X_i + Y_j - M.. = X_i + Y_j - 8.66 = 7.7$

2. Let $X_i = 9$.

Then

$$Y_j = 16.36 - 9 = 7.36$$

---

7 This procedure reduces the effects of random error at the possible cost of losing any real interactive information that might exist as a confound with the random error.

3. Let $X_i = 7.5$.

Then

$$Y_j = 16.36 - 7.5 = 8.86$$

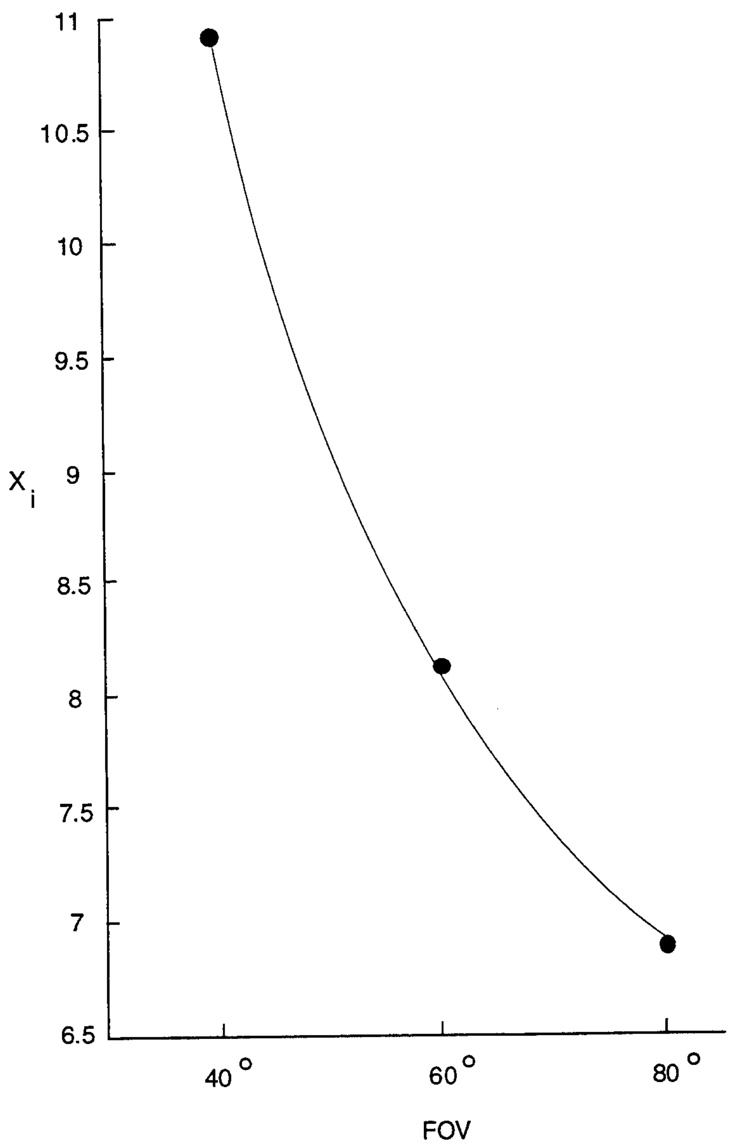


Figure 8. The plot of X_i (ordinate) versus FOV (abscissa).

4. These two pairs of values

$$(X_i = 9, Y_j = 7.36; X_i = 7.5, Y_j = 8.86)$$

are used to draw the straight line plot of the equation

$$X_i + Y_j - 8.66 - 7.7 = 0$$

$$X_i + Y_j - .96 = 0$$

This is depicted in Figure 10.

5. Select any point on the straight line in Figure 10 and read the corresponding values of $\hat{X}_i$ and $\hat{Y}_j$. Use these values in Figures 8 and 9, respectively, to obtain one pair of resolution level by FOV level that yields a D_{ij} of 7.7. For other pairs, select other points on the straight line plot given in Figure 10, read the corresponding $\hat{X}_i$ and $\hat{Y}_j$ values, go to Figures 8 and 9, and read the corresponding pair of FOV level by resolution level that yields a D_{ij} of 7.7. One could repeat this process to obtain a set of pairs of FOV level by resolution level, all yielding a D_{ij} of 7.7. Finally, one could use these pairs to construct a curve giving the locus of all pairs yielding a D_{ij} of 7.7. This is the trade-off function for an estimated error value of 7.7.

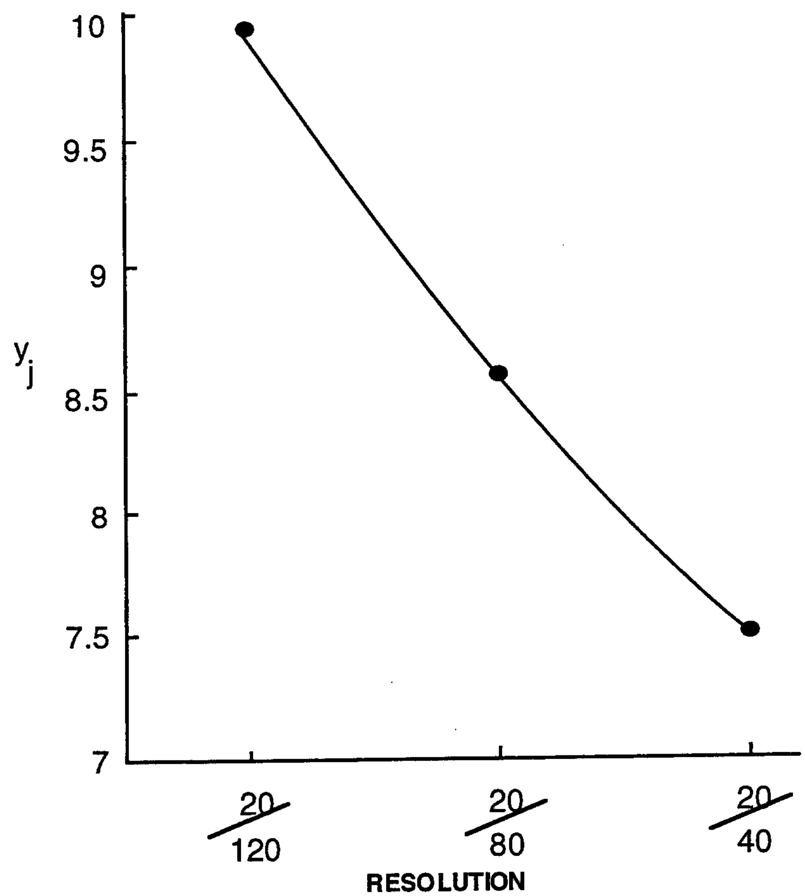


Figure 9. The plot of Y_j (ordinate) versus resolution (abscissa).

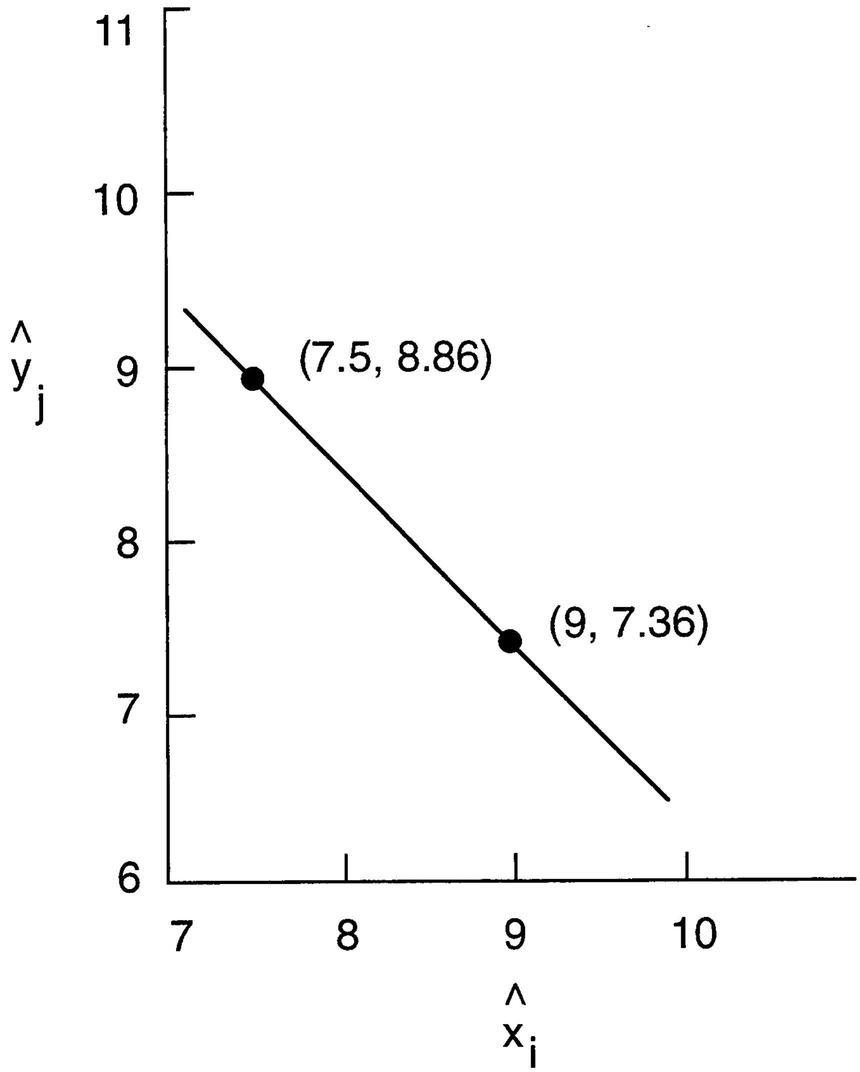


Figure 10. The plot of the equation.

There will be a separate function for each level of D_{ij}. The X_i versus Y_j plots will all be linear and parallel to the one shown.

Example 2.

Given a goggle with a resolution level of 20/100, for example, determine the FOV level that would be required to yield an estimated error level of 7.75.

1. From Figure 9, X_i for 20/100 is 9.25
2. From equation $D_{ij} = X_i + Y_j - M..$, substitute the known values

   $7.75 = 9.25 + Yi - 8.66$

$Y_j = 7.16$

3. From Figure 8, use $Y_j = 7.16$ to determine the required FOV level of 77°.

The trade-off functions have been developed with mobility errors, the dependent variable used as the criterion for establishing the trade-off relations obtained. Precisely the same procedures can be used to obtain corresponding trade-off relation for FOV and resolution using the time or rating dependent variable as the criterion. The resulting trade-off functions will differ to some extent from each other since the three dependent variables are not perfectly correlated.

CONCLUSION

The purpose of the present study was to use a quantitative methodology, based on objective observations and subjective ratings and rankings, to determine the trade-off function between resolution and FOV with respect to specific task elements inherent in traversing off-road terrain on foot. Another objective was to obtain data about the relative importance of resolution at various FOVs.

The data collected in this study were used to develop quantitative trade-off functions so that, given any combination of resolution and FOV within the tested range of these factors, one can estimate their relative performance effects on traversing off-road terrain on foot, using night vision goggles.

The results of the study indicated that a reduction in the resolution of the goggles had less impact on mobility errors with the wider (60° and 80°) FOVs than with the smaller (40°) FOV. For all dependent measures, decreasing FOV had the most impact on performance at the lowest (20/120) level of resolution.

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APPENDIX A

QUESTIONNAIRE A

Questionnaire A

On the following scales, circle the number that best represents your response.

Rate how well the goggles performed in helping you to see ground-level hazards such as stones, fallen logs, holes, roots, and streams.

1 2 3 4 5 6 7

(no forewarning) (timely warning)

Rate how well the goggles performed in helping you to see eye-level hazards such as trees, branches, wires, poles, and vines.

1 2 3 4 5 6 7

(no forewarning) (timely warning)

Rate how well the goggles performed in helping you to see terrain contour hazards irregularities such as berms, side slopes, gullies, ditches, and cliffs.

1 2 3 4 5 6 7

(no forewarning) (timely warning)

Rate how easy it was to detect the targets with the goggles.

1 2 3 4 5 6 7

(difficult) (easy)

Rate how confident you felt walking around while wearing the goggles.

1 2 3 4 5 6 7

(hesitant) (confident)

Indicate the level of visual comfort (freedom from eye-strain, blurred vision, etc.) you experienced with the goggles.

1	2	3	4	5	6	7
(none)						(continuous)

How often did the goggles allow adequate time to avoid the terrain hazards?

1	2	3	4	5	6	7
(never)						(always)

APPENDIX B

DETAILED INFORMATION CONCERNING
NVG SIMULATORS CONSTRUCTION

DETAILED INFORMATION CONCERNING NVG SIMULATORS CONSTRUCTION

FOV Simulation Method

To determine the size of the circular hole that produced the required FOV for a given simulator goggle type, three lights were set up 16 feet apart along a horizontal line at eye height, spanning 32 feet total width on the side of a building. To mark the limits of the FOV aperture on the goggle visor, the center light in this line of three lights was first fixated with both eyes open, to center the head and goggle on the line of sight straight forward, using the viewing distances shown in Table B-1. Without moving the head, each outside light was then fixated in turn, and its relative position on the visor was marked with a colored marking pen; these positions determined the aperture diameter in this axis for a given FOV. This procedure was performed for all three FOVs, and then the entire process was repeated with the head rotated 90° sideways so that the vertical axis could be determined for each FOV. This "side-looking" method avoided the practical problems associated with making vertical measurements. This procedure resulted in apertures that defined the FOV over which the eye could fixate (or foveate). One should note that the instantaneous (or "peripheral") FOV presented to the eye in each case was somewhat greater than the nominal foveal FOV. The overall change in the instaneous FOV is negligible with eye rotation because as one side of the FOV is diminished when the eye rotates, the opposite side is increased by nearly the same amount.

A spot check was recently performed to clarify the issue of the foveal versus the peripheral FOV of the simulators. This exercise involved three FOV simulators (with nominally 40°, 60°, and 80° FOVs, respectively) and two experienced subjects. For each nominal FOV simulator, each subject was measured twice for foveal and peripheral FOV in both the horizontal and vertical directions. Each individual's average results tracked the other's to within 6%. The following results represent the average of both observers over both directions:

NOMINAL SIMULATOR FOV	FOVEAL FOV	PERIPHERAL FOV
40 DEGREES	43 DEGREES	53 DEGREES
60 DEGREES	58 DEGREES	68 DEGREES
80 DEGREES	85 DEGREES	95 DEGREES

Table B-1

Viewing Distances

HALF Width (ft)	HALF angle (deg)	VIEW distance	FOV (deg)
16.0	20	44.0	40
16.0	30	27.7	60
16.0	40	19.1	80

Opaque material with a hole for the size of the FOV circle was then positioned in front of each eye position on the ski goggle lens, which was covered with two layers of green filter material, as described. This created a circular green FOV for each eye, with a small piece of opaque material (septum) fitted at the nose bridge to prevent the left eye from seeing sideways over to the hole for the right eye, and vice versa. Opaque tape was placed on the porous upper foam pad of the simulators' forehead piece to prevent glare resulting from penetration of the foam pad by direct sunlight.

Resolution Simulation Method

To simulate the three levels of resolution, visual acuity measures were used to determine how many layers of visual acuity reducing filter material would be used. These materials are mild optical diffusers, similar to those used for window envelopes; they have good low-pass modulation transfer function (MTF) spatial filtering properties (large areas are not washed out, as is the case with scattering filter materials). To obtain the required three levels of resolution, a standard visual acuity eye chart was viewed from a distance of 20 feet. Two types of eye charts were used, one with standard letters (Bausch & Lomb 713593-101ND), and one with double broken Landolt rings (Bausch & Lomb 713599-101ND).

Differences Between the NVG Simulators and Actual NVGs

In actual NVGs, an objective lens forms a real image of the scene on the image intensifier, and an eyepiece allows the observer's eye to see the resulting intensified image as approximately "life size" (same retinal size as if the scene were viewed directly with the goggles taken away, not magnified or minified).

Depth of Field

In the simulator goggles, a simple circular aperture replaces the optics of the actual NVG. When the observer looks through this aperture, the observer's eye focuses at various distances in the scene (as is normal in everyday direct viewing), whereas in looking at the intensified image on an actual NVG goggle, the scene focus distance is determined by the objective lens on the NVG, with a certain limited depth of field (range of acceptable focus sharpness) in the scene. Only an auto-focus NVG would duplicate this ability to automatically shift objective focus distance while walking. In using current operational NVGs, the observer has to manually change focus for different distances in the scene by twisting the objective lens ring on the front of the NVG. This aspect could not be practically incorporated into the simulators, since adequate optics were not available for the 60° and 80° FOVs. This limitation was not judged to significantly compromise the objectives of the experiment.

APPENDIX C

LANE WALKER'S SCORE SHEET

NIGHT VISION GOGGLES -- DATA SHEET

CONTACT WITH
EYE-LEVEL
HAZARD

CONTACT WITH
GROUND-LEVEL
HAZARD

TARGET DETECTION

(1)

(2)

(3)

(4)

(5)

(6)

(7)

CONTACT WITH
TERRAIN CONTOUR
HAZARD

MARKED
50% DECREASE
IN WALKING PACE

REQUEST FOR
ASSISTANCE

STOP

STUMBLE

OTHER

Course		Goggles		Moonlight		Group		Participant's Identification	
START TIME		END TIME		DATE		Participant's Name			

APPENDIX D

QUESTIONNAIRE B

Questionnaire B

A Comparison Among the Three Goggles

Write "best" under the best of the three goggles; write "worst" under the worst of the three goggles on the following qualities.

	Goggle 1	Goggle 2	Goggle 3
(1) Depth Perception	_______	_______	_______
(2) Level of Comfort	_______	_______	_______
(3) Target Detection	_______	_______	_______
(4) Hazard Detection	_______	_______	_______
(5) Environmental Awareness	_______	_______	_______

(6) Write "best" under your first choice of goggles to wear during a night mission; write "worst" under your last choice.

	Goggle 1	Goggle 2	Goggle 3
Choices	_______	_______	_______

(7) For each time frame, write the number of times your wore night vision goggles; enter zero if you did not wear goggles during the time frame.

__ I wore goggles in January 1995

__ I wore goggles in December 1994.

__ I wore goggles within the last year, but not since November 1994.

__ I wore goggles over one year ago.

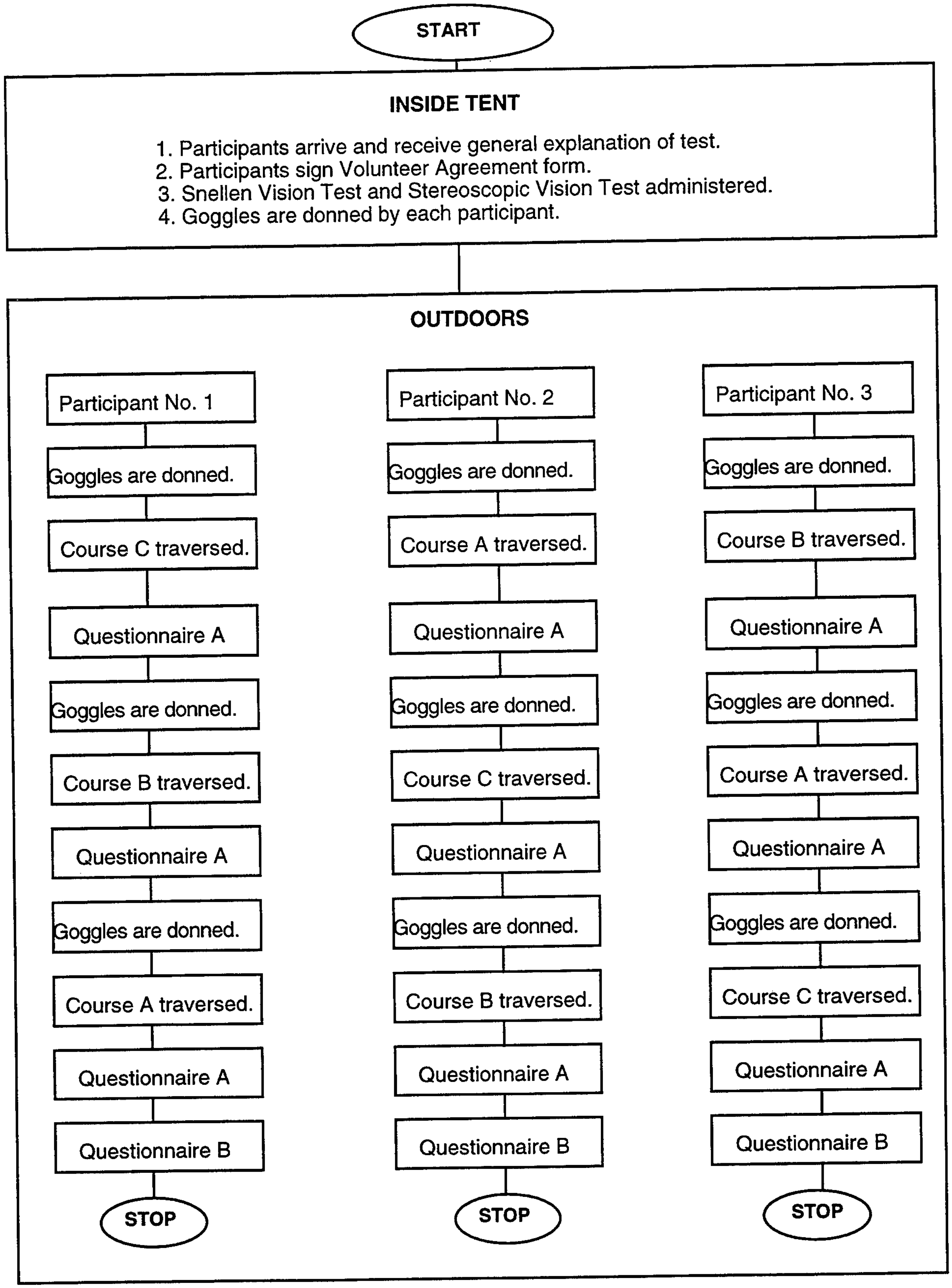
(8) Write any additional comments about the strong points or shortcomings of the different goggles or problems that are common to all three goggles.

(Use the other side of the page if necessary.)

APPENDIX E

TEST SEQUENCE

SEQUENCE OF TEST SESSION



APPENDIX F

SIMPLE MAIN EFFECTS

Simple Main Effects: Errors

Field of view (deg.)	Resolution: 20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .01
60	Goggle 7	Goggle 2	Goggle 5	p= .57
80	Goggle 6	Goggle 8	Goggle 3	p= .89
Main effect of FOV	p= .62	p= .05	p= .00*	

* p < .001

Simple Main Effects: Time

Field of view (deg.)	Resolution: 20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .22
60	Goggle 7	Goggle 2	Goggle 5	p= .03
80	Goggle 6	Goggle 8	Goggle 3	p= .93
Main effect of FOV	p= .38	p= .04	p= .04	

* p < .001

Simple Main Effects: Ratings

Field of view (deg.)	Resolution 20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .00*
60	Goggle 7	Goggle 2	Goggle 5	p= .35
80	Goggle 6	Goggle 8	Goggle 3	p= .00*
Main effect of FOV	p= .39	p= .26	p= .00*	

* p < .001

Simple Main Effects: Targets

Field of view (deg.)	Resolution 20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .01
60	Goggle 7	Goggle 2	Goggle 5	p= .17
80	Goggle 6	Goggle 8	Goggle 3	p= .23
Main effect of FOV	p= .34	p= .21	p= .04	

* p < .001

Simple Main Effects: Eye-Level Errors

Field of view (deg.)	Resolution 20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .00*
60	Goggle 7	Goggle 2	Goggle 5	p= .24
80	Goggle 6	Goggle 8	Goggle 3	p= .83
Main effect of FOV	p= .64	p= .11	p= .01	

* p < .001

Simple Main Effects: Ground-Level Errors

Field of view (deg.)	Resolution 20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .08
60	Goggle 7	Goggle 2	Goggle 5	p= .95
80	Goggle 6	Goggle 8	Goggle 3	p= .67
Main effect of FOV	p= .88	p= .82	p= .02	

* p < .001

Simple Main Effects: Contour Errors

	Resolution			
Field of view (deg.)	20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .53
60	Goggle 7	Goggle 2	Goggle 5	p= .05
80	Goggle 6	Goggle 8	Goggle 3	p= .93
Main effect of FOV	p= .98	p= .80	p= .21	

* p < .001

Simple Main Effects: Pace Errors

	Resolution			
Field of view (deg.)	20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .22
60	Goggle 7	Goggle 2	Goggle 5	p= .73
80	Goggle 6	Goggle 8	Goggle 3	p= .73
Main effect of FOV	p= .51	p= .04	p= .88	

* p < .001

Simple Main Effects: Request-for-Assistance Errors

Field of view (deg.)	20/40	Resolution 20/80	20/120	of resolution	Main effect
40		Goggle 1	Goggle 4	Goggle 9	p= .23
60		Goggle 7	Goggle 2	Goggle 5	p= .72
80		Goggle 6	Goggle 8	Goggle 3	p= .72
Main effect of FOV		p= .54	p= .65	p= .95	

Simple Main Effects: Stop Errors

Field of view (deg.)	20/40	Resolution 20/80	20/120	of resolution	Main effect
40		Goggle 1	Goggle 4	Goggle 9	p= .17
60		Goggle 7	Goggle 2	Goggle 5	p= .83
80		Goggle 6	Goggle 8	Goggle 3	p= .97
Main effect of FOV		p= .86	p= .39	p= .06	

Simple Main Effects: Stumble Errors

Field of view (deg.)	Resolution 20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .28
60	Goggle 7	Goggle 2	Goggle 5	p= .92
80	Goggle 6	Goggle 8	Goggle 3	p= .87
Main effect of FOV	p= .94	p= .61	p= .07	

Simple Main Effects: Other Errors

Field of view (deg.)	Resolution 20/40	20/80	20/120	Main effect of resolution
40	Goggle 1	Goggle 4	Goggle 9	p= .35
60	Goggle 7	Goggle 2	Goggle 5	p= .09
80	Goggle 6	Goggle 8	Goggle 3	p= .94
Main effect of FOV	p= .68	p= .12	p= .42	

APPENDIX G

ANALYSIS OF VARIANCE
(ERRORS)

ANALYSIS OF VARIANCE
(ERRORS)

Tests of Significance for ADJUSTED TOTAL ERRORS Using UNIQUE Sums of Squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	1480.50	81	18.28		
RES	159.27	2	79.64	4.36	.016
FOV	476.68	2	238.34	13.04	.000
ORDER	8.16	2	4.08	.22	.800
COURSE	495.72	2	247.86	13.56	.000
GROUP	15.97	2	7.98	.44	.648
RES BY FOV	114.68	2	57.34	3.14	.049
(Model)	2721.83	80	34.02	1.86	.003
(Total)	4202.33	161	26.10		

R-Squared = .648
Adjusted R-Squared = .300

APPENDIX H

ANALYSIS OF VARIANCE
(TIME)

ANALYSIS OF VARIANCE
(TIME)

Tests of Significance for TIME Using UNIQUE Sums of Squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	2990312.00	81	36917.43		
RES	219048.93	2	109524.46	2.97	.057
FOV	446593.04	2	223296.52	6.05	.004
ORDER	83396.04	2	41698.02	1.13	.328
COURSE	153781.81	2	76890.91	2.08	.131
GROUP	62902.91	2	31451.45	.85	.430
RES BY FOV	27349.59	2	13674.80	.37	.692
(Model)	4893794.00	80	61172.43	1.66	.012
(Total)	7884106.00	161	48969.60		

R-Squared = .621
Adjusted R-Squared = .246

APPENDIX I

ANALYSIS OF VARIANCE
(RATINGS)

ANALYSIS OF VARIANCE
(RATINGS)

Tests of Significance for RATINGS Using UNIQUE Sums of Squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	2841.00	81	35.07		
RES	1750.11	2	875.06	24.95	.000
FOV	779.59	2	389.80	11.11	.000
ORDER	273.00	2	136.50	3.89	.024
COURSE	25.04	2	12.52	.36	.701
GROUP	474.57	2	237.29	6.77	.002
RES BY FOV	92.70	2	46.35	1.32	.272
(Model)	7426.78	80	92.83	2.65	.000
(Total)	10267.78	161	63.78		

R-Squared = .723
Adjusted R-Squared = .450

APPENDIX J

ANALYSIS OF VARIANCE
(TARGETS)

ANALYSIS OF VARIANCE
(TARGETS)

Tests of Significance for TARGETS Using UNIQUE Sums of Squares

Source of Variation	SS	DF	MS	F	Sig of F
WITHIN+RESIDUAL	3614.50	81	44.62		
RES	469.27	2	234.64	5.26	.007
FOV	193.23	2	96.62	2.17	.121
ORDER	13.05	2	6.52	.15	.864
COURSE	1203.05	2	601.52	13.48	.000
GROUP	397.71	2	198.85	4.46	.015
RES BY FOV	198.90	2	99.45	2.23	.114
(Model)	5252.72	80	65.66	1.47	.042
(Total)	8867.22	161	55.08		

R-Squared = .592
Adjusted R-Squared = .190

APPENDIX K

MEANS OF EACH QUESTIONNAIRE A RATINGS
ACROSS RESOLUTION AND FOV

MEAN RATINGS ACROSS TEST PARTICIPANT
FOR EACH QUESTIONNAIRE A ITEM

Table K-1

FOV	40^{o}			60^{o}			80^{o}		
Resol.	20/40	20/80	20/120	20/40	20/80	20/120	20/40	20/80	20/120
Ratings*									
1	5.56	4.67	3.33	5.78	5.44	5.17	6.11	4.72	5.44
2	5.78	5.11	3.72	5.89	5.22	5.33	6.44	4.89	5.50
3	5.72	4.89	3.50	5.72	5.11	5.17	6.22	4.61	5.22
4	5.44	4.39	3.06	5.00	5.06	4.33	5.39	4.17	5.11
5	5.39	4.56	3.28	6.00	5.11	4.89	6.22	4.94	5.11
6	5.17	4.72	3.94	4.17	5.00	4.33	5.17	4.22	4.67
7	5.56	4.50	3.56	5.83	5.28	5.28	6.11	4.56	5.56

* 1 Perception of ground level hazards
2 Perception of eye level hazards
3 Perception of terrain contour
4 Target detection
5 Confidence in goggles
6 Visual comfort
7 Timeliness of hazard perception

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13. ABSTRACT *(Maximum 200 words)*

A field experiment was conducted to gain insight into the trade-offs between field of view (FOV) and resolution, with reference to the off-road mobility and target-detection capability of personnel using night vision goggles. Daytime simulators of night vision goggles were developed to represent all combinations of three levels of resolution (equivalent to 20/40, 20/80, and 20/120 Snellen acuities) and three FOVs (40°, 60°, and 80°). One product of the experiment was the formulation of a function that could be used to estimate human performance in traversing off-road terrain on foot. This trade-off function allows for the estimation of performance associated with any combination of resolution and FOV within the tested range. Another result was the identification of a significant interaction between FOV and resolution; for mobility errors, the effect of changes in resolution on performance increased as FOV decreased. For all dependent measures (errors, time, ratings, and targets), decreasing FOV had the most impact at the lowest level of resolution.

14. SUBJECT TERMS
field of view; night vision goggles; resolution; human target detection; ocular configuration; third generation intensifier; monocular; off-road mobility; trade-off function

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